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Modeling different urban change trajectories and their trade-offs with food production in Jiangsu Province, China

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ABSTRACT

Urban areas in China have expanded rapidly in recent decades, which mainly resulted in the conversion of fertile cropland. As the growth of urban areas is likely to continue in the next decades, there is a need for detailed assessments of urbanization impacts on food production. However, most land use models cannot simulate different types of urban change trajectories, such as expansion and densification, which constrains their capacity to inform such assessments with sufficient detail on the patterns of urbanization. In this paper, we present a land use model that represents multiple types of settlements, which allows to simulate multiple different urban change trajectories. We applied this model to Jiangsu Province, China, and assess the impact of projected urban development between 2015 and 2030 on cropland area and crop production. Results show that population growth is accommodated by different urban change trajectories, depending on the absence or presence of land use policies to maintain food security. In the absence of policies, population growth mainly leads to urban expansion, yielding losses in both cropland area and crop production. Implementing strict cropland protection policies leads to more urban densification and all population can be accommodated without a net loss of cropland. Yet, crop production decreases in this scenario as the most productive croplands are still converted and compensated by less productive areas. Protecting crop production instead leads to a small loss in cropland area combined with cropland intensification and different types of urban change, but maintains the total crop production. These results show the relevance of more nuanced representation of urban development in land use models in order to inform land use policies.

1. Introduction

Since the 1980s, the population growth and economic development in China has led to an unprecedented competition between multiple demands for land (Bai, Shi, & Liu, 2014; Chen, Liu, & Lu, 2016; Deng, Huang, Rozelle, Zhang, & Li, 2015). This competition is not unique to China and is exemplary for many densely populated delta regions that experience economic growth, population growth while being key to global food production (van Vliet, Eitelberg, & Verburg, 2017). The developments in China, therefore, allow the exploration of the consequences and possible mitigation strategies that may inform many other areas. The competing demands in Eastern China relate to different land uses, such as for residential areas for housing the population, croplands for food production, industrial areas for economic activities, and natural areas for conserving ecosystem services (Ke et al., 2018; Song & Deng, 2017). Between 1980 and 2015 China changed from a predominantly rural to a predominantly urban society, while the total population increased from 1.0 billion to 1.4 billion in the same period (National Bureau of Statistics of China, 2016). To house the increasing population and to facilitate this rural-to-urban migration, the total built-up land in China increased from 7438 km^2 to 45,566 km^2 between 1981 and 2012 (Chen et al., 2016). Since much of this new urban land is developed on former croplands (He et al., 2013), this development has intensified the competition with other land uses. Due to the ongoing rural-to-urban migration and economic development, urban areas in China are expected to continue growing in the near future. As most of the urban growth takes place in fertile cropland areas, these developments are likely to affect food production and thus food security (van Vliet et al., 2017).

To cope with these concerns, the Chinese central government has implemented a number of policies since the end of the twentieth century (Liu, Fang, & Li, 2014). The Cropland Dynamic Balance Policy has

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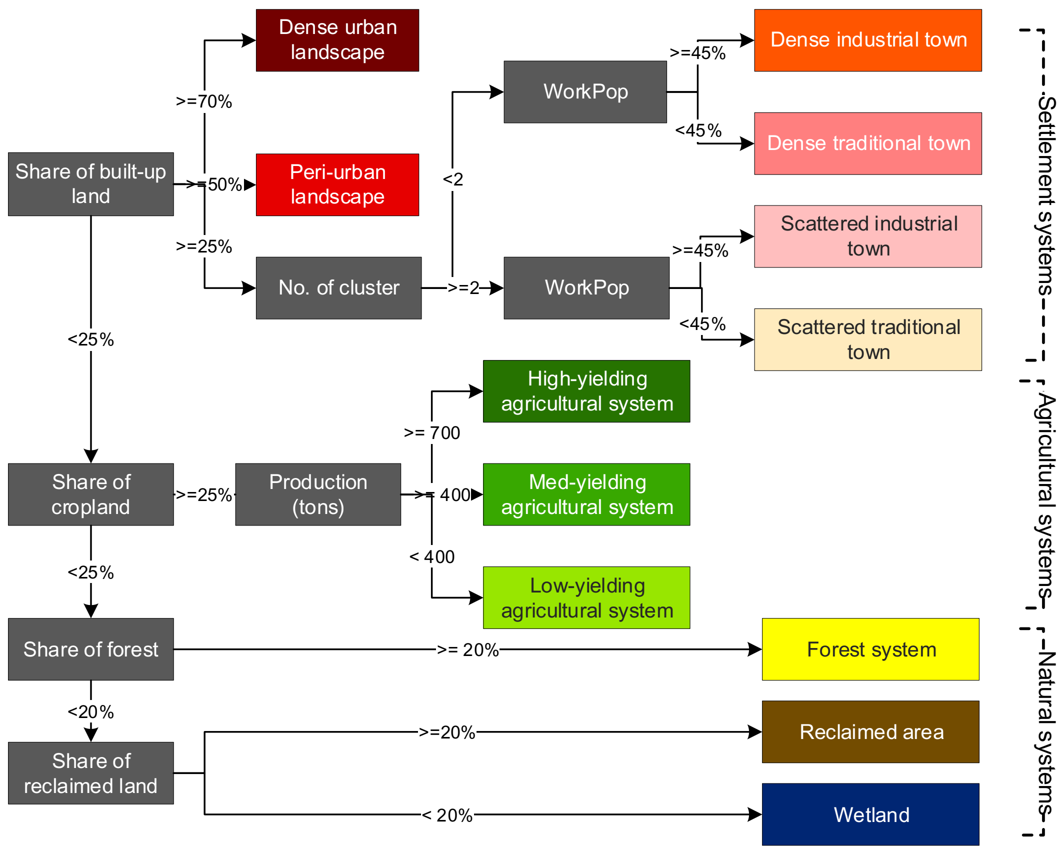

Fig. 1. Classification tree for the characterization of land systems in Jiangsu. Gray cells depend on input data and colored cells indicate the resulting land systems.

been implemented since 1996 (Cheng et al., 2015) to maintain the quantity, quality and output capacity of cropland across the country. A series of different regulations are included in this policy, such as the "requisition-compensation balance of cropland" that started in 1999, the "increasing vs. decreasing balance of urban-rural built-up land" that started in 2000, and the "economical and intensive land use" policy that started in 2014 (Liu et al., 2014). At the same time, the General Land Use Plan (national level) was released in 1999, which also aims at controlling land use change. The General Land Use Plan is subject to a system of graded examination and approval at multiple administrative levels. One of its main planning goals is to control and manage the conversion of rural land into urban land, which includes a maximum area of land that could be converted from cropland to other uses (GOSC (General Office of the State Concil of China), 1999; Zhong et al., 2018). In addition to policies that focus on cropland protection, a number of policies have been implemented that specifically address urbanization. The National New-type Urbanization Plan (2014–2020) was released by the Central Committee of the Communist Party of China (CPC) and the State Council in 2014 (Wang, Hui, Choguill, & Jia, 2015). This plan revealed a new path for urbanization that accommodated unique Chinese characteristics, including a partial relaxation of the strict urban registration (hukou) rules, and a move towards people-oriented urbanization while accounting for expected consequences for rural areas and rural land (Chen et al., 2016; Wang et al., 2015).

In order to analyze the interaction between urban growth and cropland use, as well as to assess potential future land use change trajectories, a large number of land-use models have been applied, especially for China (He et al., 2013; He, Okada, Zhang, Shi, & Zhang, 2006; Jiang, Deng, & Seto, 2012; Ke et al., 2018). However, land use changes in existing models typically reflect land cover conversions, such as from cropland to urban land, while more nuanced changes between different types of settlements or different types of cropland management are ignored (van Vliet, Verburg, Grădinaru, & Hersperger, 2019). As a result, the competition between multiple land uses is represented as a zero-sum game: if one type expands, another land use type needs to decrease by an equal amount of area (Verburg et al., 2019). Yet, in reality, land uses can change in their extent but also in their intensity, thus allowing for multiple different change trajectories in response to an increase in demand. For cropland this could lead to agricultural intensification instead of cropland expansion, i.e. producing a larger amount of crops per unit land (Kuemmerle et al., 2013). These developments have been responsible for the vast majority of the recent increase in food production, and these processes have been included in a number of recent land use change assessments (Eitelberg, van Vliet, Doelman, Stehfest, & Verburg, 2016; van Asselen & Verburg, 2013). Similarly, for urban areas this could lead to an increase in population density, instead of urban expansion. However, despite the wide range in urban form and types, such dynamics have not been included in urban growth models yet (van Vliet et al., 2019).

The aim of this study is to analyze alternative trajectories of changes in human settlements and agricultural systems in Jiangsu province, China P.R., under different population scenarios and agricultural policies. To address this goal, we classified land systems in Jiangsu using a gradient of urban intensity and agricultural intensity. Subsequently, we explored different land use change scenarios using a land use model that simulates changes in area as well as intensity of both agricultural and urban land uses. Based on the results of six scenarios, we discuss the effectiveness of different cropland protection policies to maintain food security.

2. Methodology

2.1. Jiangsu province, China

Jiangsu Province is located on the eastern coast of China, between 30°45′ and 35°20′ North, and 116°18′ and 121°57′ East. The topography is dominated by flat and fertile plains, shaped by sediments from the Yangtze River, the Huai River and the ancient Yellow River (between 1128 and 1895). In 2015, the province contained 3.4% of China's cropland, while it generated 5.7% of the crop production. Jiangsu was also home to 5.8% of China's population and it ranks second of all provinces when measured by the size of the economy. In recent decades, the province has experienced rapid urbanization, exceeding China's average urbanization rates (Lu, Shi, Chen, & Yu, 2017; National Bureau of Statistics of China, 2016). This development is the result of natural population growth in combination with migration originating elsewhere within China. As a result of the presence of fertile soils and recent population growth, the vast majority of the province is currently in use as either agricultural land or urban land, leaving little room for expansion of either (Lu et al., 2017).

2.2. Land system classification

We developed an expert-based classification that characterizes Jiangsu in three major groups of land systems (settlement systems, agricultural systems and natural systems, see (Fig. 1), based on a combination of land cover, cropland productivity, and the economic sector in which the population is employed. The land system classification is developed to explicitly include a gradient in settlement systems, ranging from town systems to dense urban areas. This gradient reflects the variety in settlement systems that has been observed in reality (Li, van Vliet, Ke, & Verburg, 2019) and that allows simulating incremental urbanization processes that are typically found in China.

Land systems were identified at a 1 km^2 resolution, integrating multiple data sources (Table 1). All input data was first aggregated to a 1 km^2 resolution and subsequently included in the classification tree (Fig. 1). Based on the share of built-up land in a pixel we first classified dense urban landscapes and peri-urban landscapes. Subsequently, we used the share of built-up land, in combination with the number of clusters of built-up land and the share of the population working in the industry and services to identify four different types of town landscapes. The latter was included to reflect the drastically different characteristics of traditional (agriculturally oriented) settlements, and newer settlements that are oriented towards services and industrial activities (Long, Liu, Wu, & Dong, 2009; Ma & Fan, 1994; Wei & Fan, 2000). Cropland productivity was quantified by the annual crop production in each pixel, which is derived from crop production data at the town level in combination with multi-cropping frequencies. As this data is only available at the town level, we assumed that the productivity is homogenous within each town. Natural systems were divided into forest systems, reclaimed area, and wetlands, based on the land cover distribution in a pixel. Reclaimed area is an important reserve resource for potential future land use, and Jiangsu has a limited but valuable amount of reclaimed coastal land which provides opportunities for the development of new cropland areas (Cai, van Vliet, Verburg, & Pu, 2017; Ma et al., 2014).

2.3. Modeling urban growth

We used the CLUMondo model to simulate changes in land systems under different scenarios (van Asselen & Verburg, 2013). In this model, land systems change in respond to various demands for goods and services provided by these land systems. These changes are allocated based on a series of socio-economic and biophysical variables, in combination with conversion rules indicating what conversion are allowed and the resistance of land systems to convert. The allocation

Table 1
Input data for the land system classification and characterization. Data listed here coincides with those shown in Fig. 1.

Dataset	Reference	Year	Resolution	Processing
Land cover	CLUDs provided by Chinese Academy of Science (http://www.resdc.cn/)	2015	30 m	Classes 51 and 52 are included in built-up land, classes 11 and 12 are included as cultivated land, classes 21, 22, 23 and 24 are included as forest, classes 31, 32, 33, 41, 42, 43, 45, 46, 63, 64, 65, 66 and 67 are included as wetland (grassland and bare land are included in wetlands because these mainly exist on tidal flats and along rivers in Jiangsu). All are expressed as the percentage of a 1 km^2 pixel.
Reclaimed land	Department of Land and Resources of Jiangsu Province	2015	Polygons	Polygons are converted to raster and values are expressed as the percentage of each pixel covered with reclaimed land.
Employment (WorkPop)	Jiangsu statistical year book (2016)	2015	Town level	Persons is employed in industry and services.
Production	Jiangsu statistical year book (2016), SPOT-VGT as processed by Chinese Academy of Science (http://www.resdc.cn)	2015	Town level, 1 km^2	Crop production is reported at the town level, and subsequently downscaled proportional to the amount of harvested area, which is derived from the amount of cropland per pixel and the amount of harvests per year (using peaks in NDVI from SPOT-VGT).

Table 2
The services provided by each land system.

Land system	Population (persons/pixel)	Cropland area (km^2/pixel)	Crop production (tons/pixel)
Dense urban landscape	5503	0.076	40.2
Peri-urban landscape	2416	0.296	193.5
Clustered industrial town	1740	0.361	222.1
Clustered traditional town	1208	0.422	335.5
Spread industrial town	975	0.462	311.8
Spread traditional town	586	0.482	404.2
High yielding agricultural system	168	0.594	652.1
Med-yielding agricultural system	212	0.592	426.7
Low-yielding agricultural system	294	0.564	231.8
Forest	124	0.015	6.38
Reclaimed area	15	0.002	0.55
Wetland	41	0.006	2.98

mechanism uses an iterative procedure to allocate land systems in order to meet these demands by optimizing the total suitability of the land allocated to different uses. The location suitabilities for the different land systems are based on relations between socio-economic and biophysical variables and the current allocation of land systems using logistic regression analysis.

The unique property of CLUMondo is that the same demand for goods and services can be fulfilled by multiple different land systems, and that also each land system can provide multiple different demands (van Asselen & Verburg, 2013). This allows, in contrast to other land use models, the evaluation of alternative land system change trajectories to fulfill these demands. In this application we use 'residence for population' as a demand driving urban development and crop production or cropland area as a demand driving changes in agricultural systems, depending on the scenario and associated policy targets.

All land systems are characterized in terms of their population, cropland area and crop production (See Table 2). This characterization is based on data of population distribution, cropland area and crop production as shown in Table 1. For each land system, the value of a property is calculated as the average of all pixels classified into that class. For example, the population in a pixel of a dense urban landscape is 5503, which is the average population in all pixels that are classified as dense urban landscape, according to GHS human grid (Freire, MacManus, Pesaresi, Doxsey-Whitfield, & Mills, 2016). Because the data used for this characterization is available at a fine resolution, all land systems have a value for each of these three properties. For example, also wetland areas have a population density > 0, because some pixels that are classified as wetlands have some inhabitants according to the population data. Similarly, industrial towns have a higher production than low-yielding agricultural land, despite their slightly lower cropland area, according to the empirical data underlying this classification. This characterization result can be explained by town systems being predominantly covered by relatively intensive agricultural land, while low-yielding agricultural systems are more remote and typically in less fertile or less intensively managed areas.

The characteristics of land systems, in terms of population, crop area and crop yield indicate how changes in demands can be fulfilled. For example, an increase in population for the province can lead to (a combination of) changes from land systems with a lower population to land systems with a higher population, such as from scattered traditional towns to dense traditional towns. Which of the multiple possible trajectories is chosen in a specific location depends on the suitability of that pixel for different settlement systems, the land system changes that are allowed (based on their plausibility), and the attraction of other settlements as expressed in the neighborhood effect. The latter has been identified as an important driver of urban growth due to benefits of agglomeration (Liao et al., 2016; van Vliet et al., 2013). Since almost all land in Jiangsu is either urban or agriculture, the competition for land between both can thus shape settlement trajectories, similar to this demand shaping intensification of agricultural land in other areas (Eitelberg, van Vliet, & Verburg, 2015; van Asselen & Verburg, 2013).

All model parameters and a more technical description of the model and its functioning is provided in the Supplementary material.

2.4. Land use change scenarios

We developed six scenarios to explore future urbanization trajectories and their interaction with different cropland protection policies. The scenarios differ in their projected population growth (planned and trend extrapolation) and the way cropland protection policies are implemented (no cropland policy, no net loss in cropland area, no net loss in crop production) (See Table 3). For population development the scenarios were either based on the national planning on population (2016–2030), and scaled to the province of Jiangsu (population changes in Jiangsu were proportional to population changes in all of China between 1990 and 2015), or based on trend extrapolation by linearly extrapolating of the population changes in the period 1990–2015 until 2030. Policy representation includes cropland protection scenarios that stipulate that the total area of cropland in all years between 2015 and 2030 is at least as much as in 2015, thus not allowing any net loss. This interpretation reflects the general land use plan for Jiangsu Province 2006–2020, although in reality some loss of cropland may be allowed (Jiangsu Provincial Department of Land Resources, 2010). The crop production scenarios instead stipulate that the total crop production between 2015 and 2030 cannot be lower than the crop production in 2015, regardless of the changes in cropland area.

Based on these we set two reference scenarios (S1 & S2) that have no cropland protection policies and include the planned and extrapolated population scenarios for 2030, respectively. Scenarios S3 and S4 assume a cropland area protection policy in combination the planned and trend-extrapolation developments, respectively. Scenarios S5 and S6 assume a crop production protection policy in combination the planned and trend-extrapolation developments, respectively.

2.5. Analysis of scenario results

Increased population can be accommodated by expansion of settlement systems, or by conversion to settlements with a higher

Table 3
Design of land use change scenarios for this study.

Population demand	Land use policies		
	No cropland policies	No net loss of cropland area	No net loss of crop production
Planned population change	Scenario 1 (S1)	Scenario 3 (S3)	Scenario 5 (S5)
Extrapolation of recent trend	Scenario 2 (S2)	Scenario 4 (S4)	Scenario 6 (S6)

population. Similarly, land use changes can lead to change in cropland use intensity as well as in a change in cropland area. Increases and decreases in the total area of both built-up land and cropland are denoted as expansion and contraction respectively, while increases and decreases in their intensity, such as changing production or population density per unit area, are indicated as intensification and dis-intensification (Eitelberg et al., 2015; van Asselen & Verburg, 2013). Model results were assessed by comparing the share of population and crop production changes in intensification (or dis-intensification) and expansion (or contraction) regions.

For cropland, these changes can be expressed as:

$$Crop_{int} = \sum_{i} \Delta Y_i * CL_{end_i} \tag{1}$$

$$Crop_{area} = \sum_{i} \Delta CL_i * Y_{start_i} \tag{2}$$

where the $Crop_{int}$ is the total production change due to changes in crop production intensity, $Crop_{area}$ is the total production change due to changes in cropland area, Y is the production (tons/km^2) in a cell, *CL* is the total cropland area (km^2) in a cell, and *i* indicates the cells on the map. Both Y and CL are properties of the land system in a cell, as indicated in Table 2.

For built-up areas:

$$POP_{int} = \sum_{i} \Delta pop_i * BU_{end_i} \tag{3}$$

$$POP_{area} = \sum_{i} \Delta BU_i * pop_{start_i} \tag{4}$$

where the POP_{int} is the total population change leading to changes in population intensity, POP_{area} is the total population change leading to changes in built-up land extension, *pop* is the population (persons) in a cell, *BU* is the built-up land area (km^2) in a cell, and *i* indicates the cells on the map. Both pop and BU are properties of the land system of a cell, as indicated in Table 2.

3. Results

3.1. Projected land use changes for Jiangsu

Fig. 2 shows the distribution of land systems in Jiangsu in 2015. About 11.2% of the area in the province consists of dense urban and peri-urban landscapes, and these areas are mostly concentrated in Southern Jiangsu. Together these two land systems contain almost 63% of the population. Town systems (i.e. clustered industrial towns, clustered traditional towns, spread industrial towns, and spread traditional towns) cover about 16% of Jiangsu and include 19% of its population. Industrial town systems are found predominantly in Southern Jiangsu, while most traditional town systems are found in Northern Jiangsu. Agricultural systems cover about 59% of Jiangsu and produce almost 80% of the total crop production in the province (most of the rest is produced in land systems indicated as town systems). In addition, agricultural systems also contain 17% of the population. High-yielding agricultural systems are mostly distributed in Northern Jiangsu, which is mainly formed by river sediments. Affected by human activities and soil conditions, the low-yield farming system are mainly found in Southern Jiangsu and the coastal areas. Only few forests exist in Jiangsu, and these are mostly parks and protected areas and thus unlikely to change. Along the coast, reclaimed areas cover about 2.3% of the province, while wetlands, including lakes, rivers and coastal mudflats, cover about 9.8%.

The result of scenario S1 shows that settlement systems generally increased at the cost of agricultural systems (See Fig. 2b, results of other scenarios are shown in Fig. S1). All six scenarios include a considerable amount of settlement changes to accommodate the growing population, but these changes take different forms. In reference scenarios (S1 and S2), settlement changes mainly lead to the loss of agricultural systems. In scenarios that implement area-protection policies (S3 and S4), this leads to the development of new agricultural areas along the coast, mainly on reclaimed land, to compensate for these losses of agricultural land.

Fig. 3 shows how built-up area, cropland area and crop production change under the different scenarios. S1, S3 and S5 have the same demand for population, yet differ in the expansion of built-up land, as well as in the changes of cropland and crop production. Specifically, the built-up area increase is smaller in both cropland policy scenarios, due to the increased competition for land between both urban land and cropland. Consistently, S2, S4 and S6 also have the same population, while the expansion of built-up land and the change in cropland and crop production differ considerably. From these scenarios it is also clear that the implementation of cropland protection policies reduces the expansion of built-up land and instead leads to changes to settlement systems with a higher population density.

S3 and S4 implement a no net loss policy for cropland, which therefore leads to no change in cropland, as shown in Fig. 3 (the small loss in cropland in S4 is a result of the margin that is allowed in the land use model algorithm and required for the model to find a solution). Yet, while there is no loss in cropland area, scenarios show a loss in crop production of 106 and 237 Ktons, respectively. At the same time, S5 and S6 show that a protection of crop production indeed leads to no net loss in crop production, even though the area of cropland decreases by 438 and 751 km^2, respectively.

3.2. Alternative land use change trajectories under different scenarios

Changes in population are accommodated differently in different scenarios, leading to different land use change trajectories (Fig. 4). In all scenarios, there is a net increase in dense urban landscape, peri-urban landscape, and clustered industrial towns. Moreover, all scenarios show a net decrease in clustered traditional towns, spread industrial towns and spread traditional towns. A closer look at the conversions leading to these net changes shows that settlement systems typically change incrementally, rather than suddenly. Most new dense urban landscapes were already peri-urban landscapes in 2015, most new peri-urban areas in 2030 were already clustered towns in 2015, and most new clustered towns in 2030 were already spread towns in 2015. In addition, Fig. 4 shows that while the net change might be relatively small for several settlement systems, the gross change is often much larger in no policy scenarios. This is particularly clear for spread towns, which have both a high gross loss to other settlement systems and a high gross gain from agricultural systems. At the same time, some clear differences appear. The population trend scenarios (S2, S4, and S6) all have a higher population growth than the population planning scenarios, leading to more changes towards denser urban systems (i.e. dense urban landscape, peri-urban landscape and clustered industrial towns). In scenarios with cropland area protection mechanisms in place (S3 and S4), cultivation of reclaimed coastal land is needed to meet this requirement, while this is not the case in other scenarios. In scenarios with crop production policies, on the other hand, we observe more land use intensification, in combination with more urban densification to avoid additional losses of crop production (Fig. 4).

Fig. 5 shows the relative contribution of different types of land use changes to total crop production (e.g. intensification, dis-intensification, expansion and contraction) for Jiangsu between 2015 and 2030. The sum of all bars related to a specific scenario corresponds with the net change in crop production as shown in Fig. 3. In this figure, contraction relates to the conversion of cropland into built-up area, which takes place in the transition between agricultural systems and settlement systems, but also in the conversions between different settlement systems. Similarly, changes in land use intensity can arise from changes between different agricultural systems, different settlement systems, and changes from agricultural to settlement systems. In scenarios that

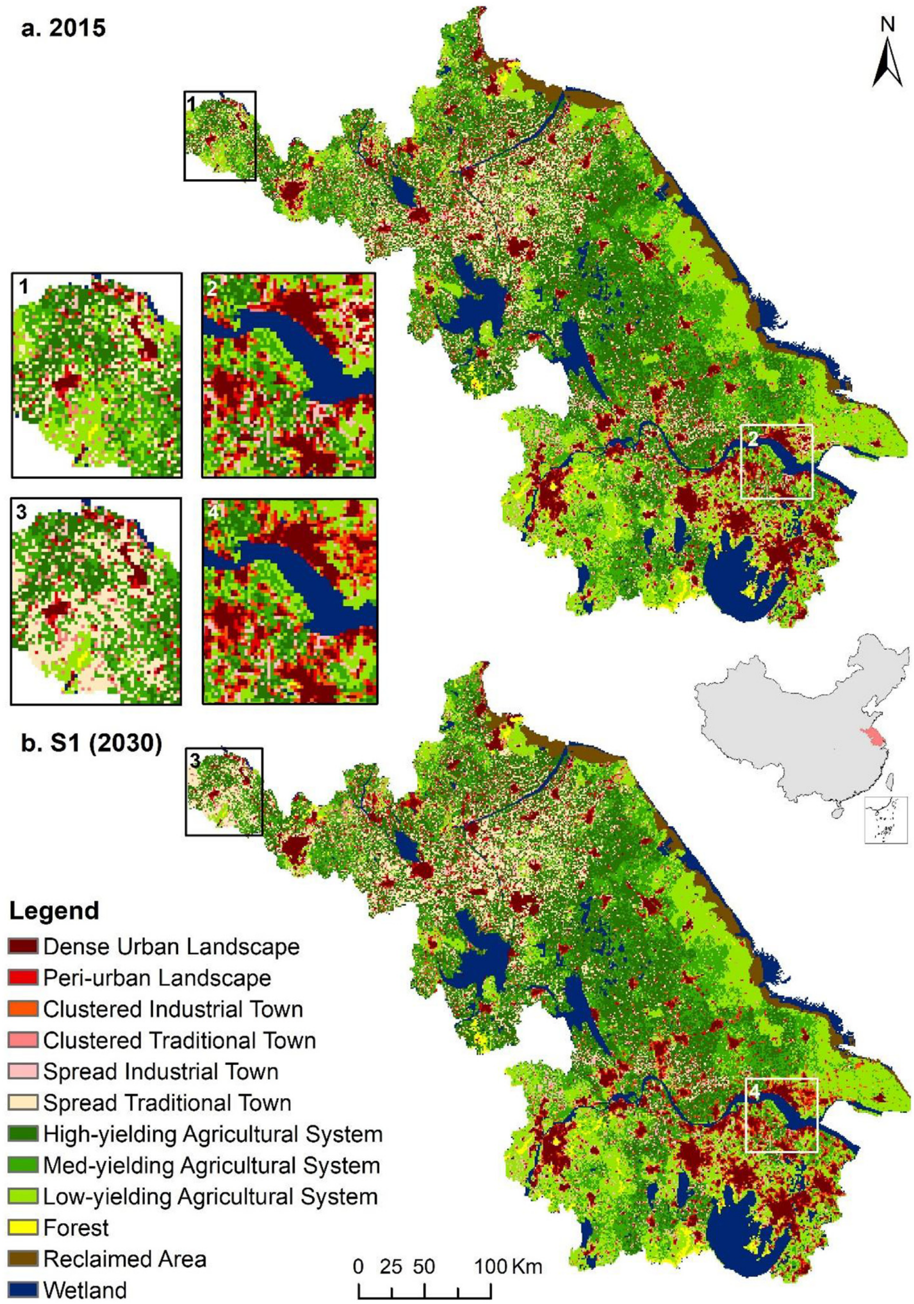

Fig. 2. Jiangsu land system map in 2015 (a) and simulated under S1 (b).

include cropland area protection (S3 and S4), there is less cropland intensification than in other scenarios, as there is no need to increase production as long as the total amount of cropland area remains constant. Conversely, in scenarios with crop production protection (S5 and S6), the highest amount of intensification is found, exactly because crop production is an explicit demand in these scenarios. For Southern Jiangsu, farming systems dis-intensify and contract in all scenarios, while little intensification is observed. Most of intensification takes place in Northern Jiangsu, which is characterized by relatively high-quality cropland. In the reference scenarios (S1 and S2) and production protection scenarios (S5 and S6), much contraction is simulated in the northwestern corner of the province, due to the expansion of settlement systems. In area protection scenarios, additional cropland expansion into coastal reclaimed land is simulated to compensate the conversion of cropland elsewhere into settlement systems.

4. Discussion

4.1. Interaction between settlement systems and agricultural systems

In the absence of any cropland protection policies, our projections show an increase of 792 km^2 and 1505 km^2 of built-up land, for the policy and the trend population scenario, respectively. This gain in built-up land comes with a net decrease of 469 km^2 and 886 km^2 of cropland, leading to a loss of 183 Kton and 494 Kton of crop production, respectively. The projected changes correspond to about 53–100 km^2 of new built-up land per year and a decrease of 31–59 km^2 of cropland per year, which is much lower than what has been observed in recent years. Between 1980 and 2010 (Huang et al., 2015) observed an average increase of 252 km^2 of built-up area in Jiangsu, and an average decrease of 273 km^2 of cropland per year. Moreover, urban expansion and loss of cropland areas was mainly concentrated in the

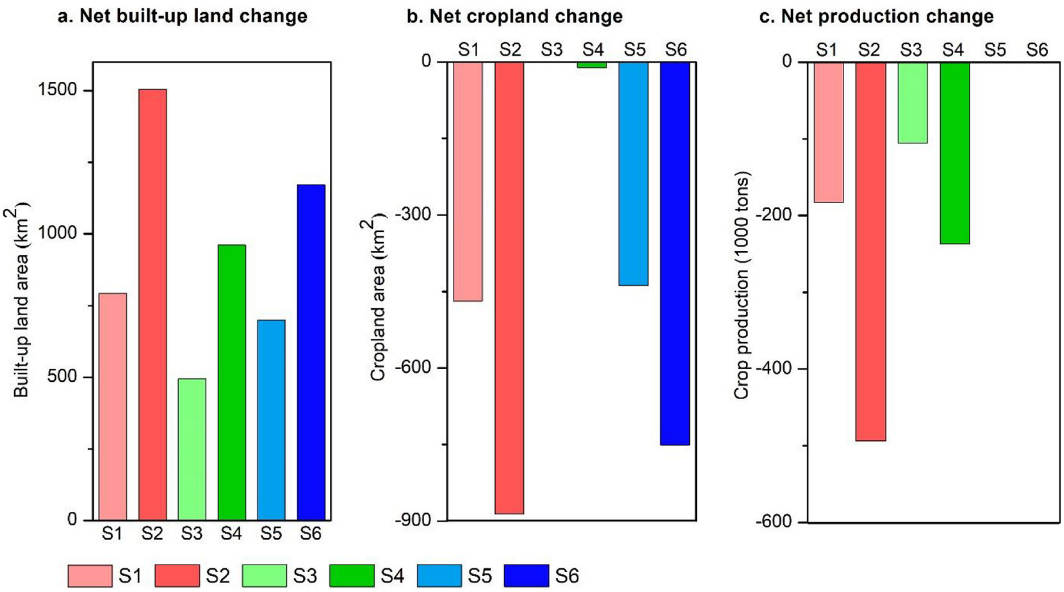

Fig. 3. Services net changes in different scenarios. Net built-up land change (a), net cropland change (b) and net crop production change (c).

period 2000–2010. These differences can partly indicate an overestimation of urban growth and cropland loss in that study, as the National Bureau of Statistics of China reports a cropland loss of only 41 km^2 per year in Jiangsu over the same period, which is comparable to our simulation results (National Bureau of Statistics of China, 2016). Another part of the difference could be explained by the increase in wealth in this part of China. In our simulation, urban development is driven by population growth only, while other studies have indicated that wealth is positively related with urban expansion due to larger area needs per person, for housing, but also for example associated facilities such as infrastructure, parking space and shopping space (e.g. (Angel, Parent, Civco, Blei, & Potere, 2011)). Since this is not included in our study, the actual amount of urban expansion might be larger than simulated in our scenarios. This means that it would be more difficult to achieve no net loss in cropland area or production under conditions of further economic growth than indicated by our results. Another factor influencing the fast increase in urban area in between 2000 and 2010 might be the rapid development in real estate for residential and economic purposes (Glaeser, Huang, Ma, & Shleifer, 2017). This increase has been characterized as a real estate boom, fueled by investment rather than demand for housing units, which makes it unlikely that urban expansion will continue to growth at this extremely high speed (Chen & Wen, 2017; Glaeser et al., 2017).

The implementation of strict cropland area protection policies could prevent any net cropland losses, as is shown in S3 and S4, while still accommodating the same population growth as in all other scenarios. There is very little space for cropland expansion within Jiangsu to compensate for cropland conversion into built-up land. Off-setting and no net loss policies worldwide suffer from this dilemma as most lands worldwide are used for some purpose already and off-setting loss of agricultural or natural lands is often complicated by this general lack of available land (Jiang, Deng, & Seto, 2013; Meyfroidt, Rudel, & Lambin, 2010). Therefore, in our study area, the implementation of these cropland protection measures primarily leads to a development of existing settlement systems towards more dense systems, reducing the land take and need for compensation (see Fig. 4). However, although no losses are projected in cropland area, these projections lead to considerable losses in crop production in this scenario. This is a result of relatively productive land converting into built-up land, in combination with reclaimed coastal land that is cultivated but with low crop production. This compensation process resembles the current implementation of the cropland dynamic balance system, which leads to the conversion of high quality cropland into industrial and residential land, which is compensated with cropland of generally lower quality (Wu, Shan, Guo, & Peng, 2017). Hence our results are consistent with findings of Wu et al. and Song & Pijanowski, who showed that China's cropland protection policies play an important role in protecting cropland area while harming the quality of cropland from theoretical comparison and the potential land productivity calculation (Song & Pijanowski, 2014; Wu et al., 2017).

Protection of crop production instead could allow losses in cropland area without losing any production capacity (Scenario V & VI). This is largely an result of preserving the most productive croplands in combination with further intensification of existing cropland. For this analysis we assumed that yields will remain constant throughout the simulation. In reality, the total production in Jiangsu has increased continuously between 1990 and 2015 (National Bureau of Statistics of China, 2016), which may be a result of different land management factors, such as an increase in cropping intensity, the application of better cultivars, or other factors, potentially enable by climate change (Erb et al., 2013; Yu et al., 2018). As intensification of cropland is likely to continue, it is also likely that our projection includes an underestimation of the total crop production, and that actually this scenario represents a gain in production, together with a loss in cropland.

A comparison of scenario results suggests that protection of the area under crop cultivation might not be the most efficient way to achieve food security and maintain a minimum level of food production. Instead, it suggests that focusing on the most productive cropland and intensifying other croplands to achieve a no net loss of crop production could be more effective, while at the same time offering space for urban expansion. This approach also allows to accommodate for both the national demand for crop products and the local demand for urban expansion (Huang, Zhang, & Liu, 2019). In its current form, the national policy to ensure food security is based on quota-oriented cropland preservation planning, which can lead to transactions between high-yielding cropland and low-yielding cropland (Wu et al., 2017; Zhong et al., 2018). This national desire to protect cropland poses a challenge for local aspirations for urban development (Wu et al., 2017). Results of our study confirm that there is a possibility both maintain food security and allow urban development, as suggested by (Song & Pijanowski, 2014). The general land use plan already partly implements this idea as it provides a minimum area of cropland that has to be preserved per county, while also emphasizing the protection of high quality cropland (e.g. basic farmland zoning) (Zhong et al., 2018).

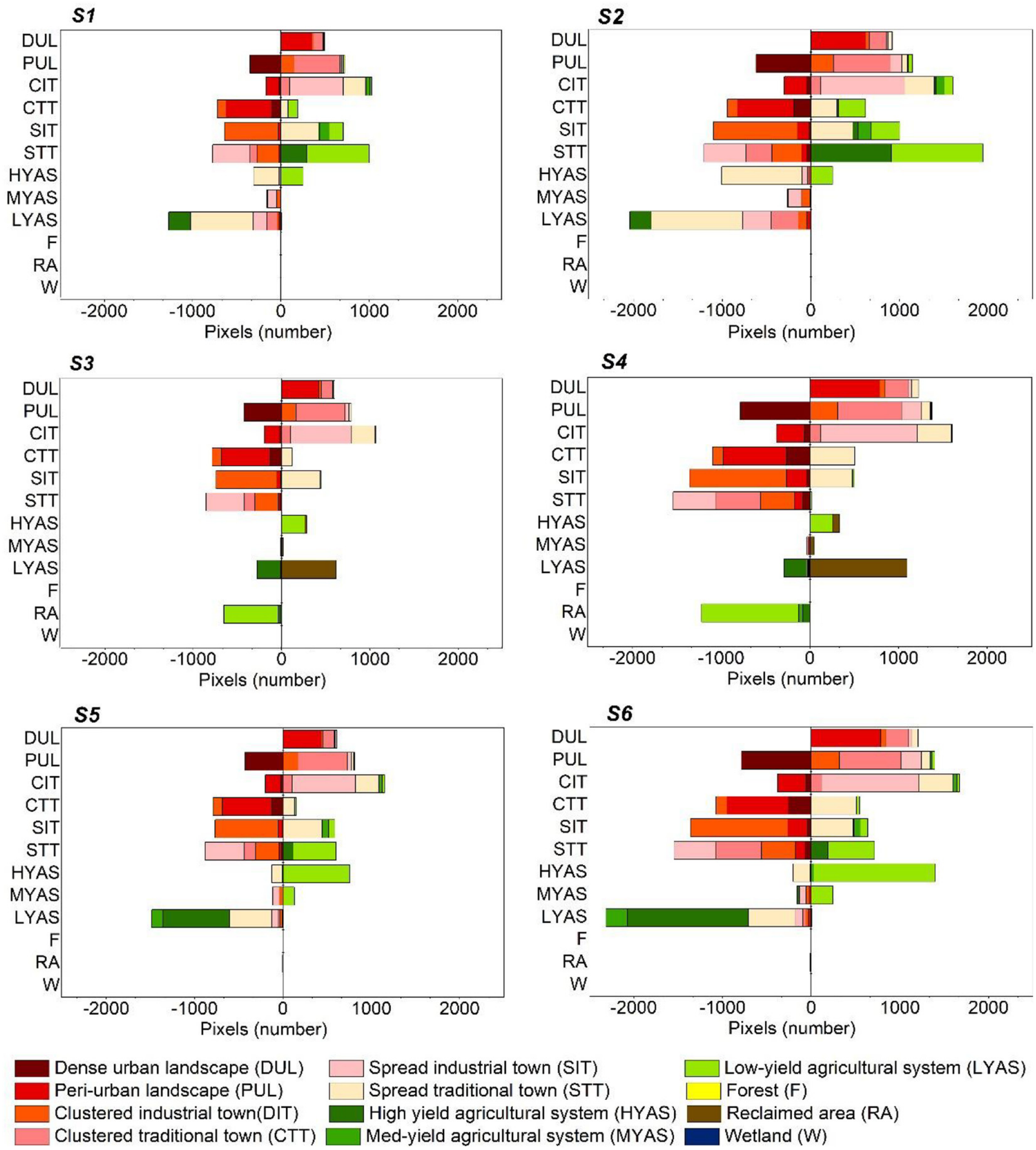

Fig. 4. Gross/net change in different land systems.

4.2. *Modeling alternative urban development trajectories*

Land use models have been applied widely for the analysis of land use change processes as well as the projection of future land use change trajectories, in order to assess potential environmental impacts or the consequences of spatial planning and land use policies (Agyemang & Silva, 2019; Dorning, Koch, Shoemaker, & Meentemeyer, 2015; Gounaridis, Chorianopoulos, & Koukoulas, 2018). These models typically represent urban land as one single class, related to the presence of built-up area (Benza, Weeks, Stow, López-Carr, & Clarke, 2016; Mustafa et al., 2018; Stow, Clarke, & Weeks, 2018). As a consequence, the simulation of urban land use change processes is limited to the conversion of non-built-up to built-up land. In this study we characterized urban land in several classes, ranging from town systems to dense urban areas. As a result of this classification, we were able to simulate the gradual development of settlements, rather than a sudden conversion.

We simulated changes in settlement systems in response to different population growth scenarios, which led to different combinations of built-up area expansion and urban intensification. These different urbanization trajectories have different impacts on the conversion of cropland and the loss of crop production. Contrary to most other existing models, the amount of built-up land is therefore a consequence, rather than an input to the model. This approach to modeling urban change in terms of land cover as well as land use intensity builds on the land systems models (Eitelberg et al., 2016; Malek, Verburg, Geijzendorffer, & Bondeau, 2018; van Asselen & Verburg, 2013), which pioneered this approach for agricultural land use intensity.

In the context of the dual urban-rural land system in China, there are large differences in population density and socio-economic activity between cities and towns, and huge differences in rural development range from north to south and west to east (Deng, Liu, Cai, Lu, & Nielsen, 2015; Liu, Feng, Yang, & You, 2010; Liu, Qi, Cao, & Liu, 2015). Therefore, we classify settlement systems based on land cover data (built-up land and number of patches of built-up land) and socio-economic data (the share of population employed in industry and services). As population densities also differ considerably between the identified settlement systems, this offers a way to simulate both urban intensification and expansion, and analyze their impact on other land uses. This classification provides a valuable reference for settlement system changes, but it comes with some limitations. In our

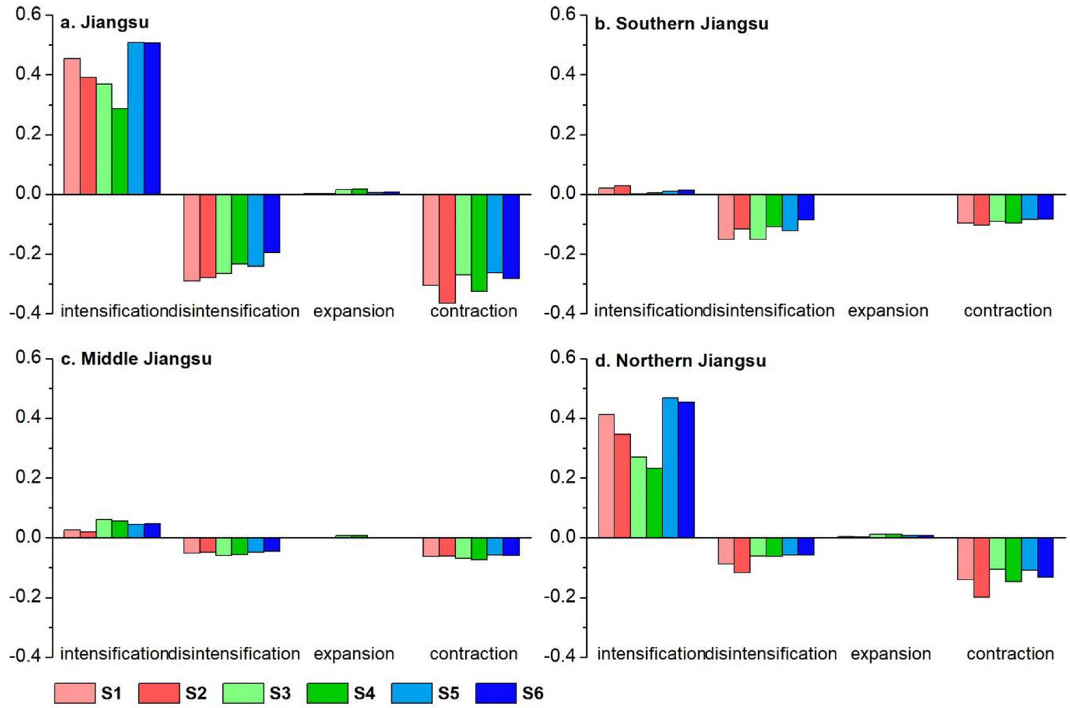

Fig. 5. Changes in cropland intensity and extent in each of the six scenarios from 2015 to 2030.

classification, the share of built-up land is the main parameter that distinguishes urban landscapes, peri-urban landscapes and towns. Therefore, the transition between settlement systems will inevitable include both intensification and expansion simultaneously, while more elaborate classifications could further differentiate between both types of development.

Population density is used in this study to represent urban land use intensity, and also as driving force steering urban expansion and intensification. Yet other metrics of urban land use intensity are possible, such as floor area and economic or social activity (e.g. Louail et al. (2014); van Vliet et al. (2019); Zhang et al. (2017)), which could greatly improve our perception of urban land use intensity and require further exploration.

China has seen rapid urban development in recent decades, and, as a consequence these processes have been analyzed in several studies, both retrospectively and forward-looking. The model application for Jiangsu province is characterized by a gradient from towns to dense urban centers, based on empirical data on built-up land and population density. In fact, recent analyses (Li et al., 2019) show that the majority of all built-up land in China is included in town systems. Yet, the relevance of representing different trajectories is not restricted to Jiangsu province or China, as differences in settlement types as well as different urban development trajectories have been reported in many world regions. For example, in the US, minorities tended to consume less space per person and live in more central neighborhoods, while white populations moved to the more sprawled suburbs (Carruthers, 2003; Paulsen, 2013). Further, Kaza revealed that urban counties became less fragmented, while rural counties in the Southern and Western United States experienced leapfrog expansion (Kaza, 2013). Also Europe has experienced a wider range of settlement change trajectories. For example, sub-urbanization processes in Germany show a tendency for people to move away from inner cities and towards the surrounding areas of cities (Jetzkowitz, Schneider, & Brunzel, 2007). In many developing countries, such as in Africa, most people live in rural areas and rural-to-urban migration is often inspired by the possibilities to earn a living, even though not all migrants are poor (Tacoli, McGranahan, & Satterthwaite, 2015). At the same time, urbanization processes in rural regions of Africa often occurs not in proximity to, but rather dis-associated from, existing urban centers (Lazaro, Agergaard, Larsen, Makindara, & Birch-Thomsen, 2019). Such settlements are generally not acknowledged as urban entities, but are involved in an administrative process (Lazaro et al., 2019). While policies to protect croplands are most pronounced in China, similar efforts are made in other parts of the world. Policies aimed at urban densification to protect open space are found in UK (e.g. the Green Belt or Green Infrastructure policy) and Netherlands (e.g. the Green Heart policy) (Amati & Taylor, 2010; Koomen, Dekkers, & van Dijk, 2008; Westerink & Aalbers, 2013). While these policies are often insufficient to stop the loss of cropland and open space to urban development they shift trends and lead to clearly different change trajectories than observed in the past. These processes illustrate the need to represent the variety in settlement systems and their different change trajectories in land use models, in order to understand the underlying processes and provide informed scenarios for future land use change developments.

Declaration of Competing Interest

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compenvurbsys.2019.101355.

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